

Information Economics in Simulation-Based Design

The MARC 266 Crowd:

Chris Paredis

Jason Aughenbaugh

Rich Malak

Jay Ling

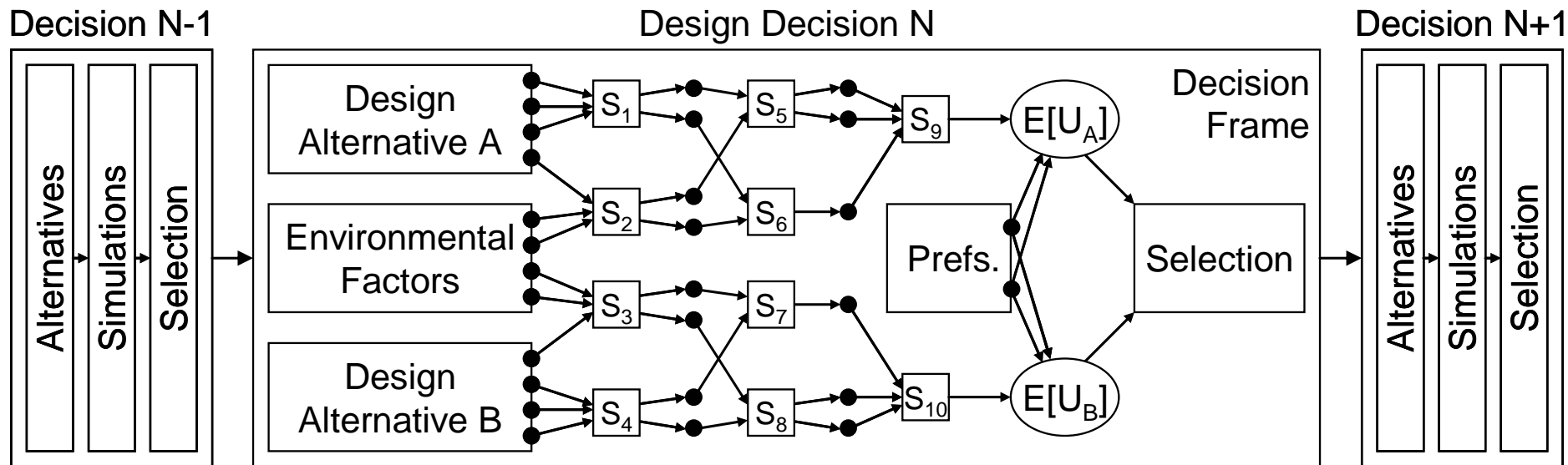
Morgan Bruns

Steve Rekuc



MARC 266/7 Research Overview

- Focus: Simulation Based Design



MARC 266/7 Research Overview

- Perspective: Information Economics

$$\begin{aligned} \text{Net Value of Decision} = \\ \text{Expected Value of the Decision Outcome} \\ - \text{Cost of Framing and Solving the Decision Problem} \end{aligned}$$

- Additional Theme: Representation of Uncertainty:
 - When the uncertainty is large, it may be valuable to represent it as an **Imprecise Probability**
 - Uncertainty is often large at the early stages of design, or when trying to characterize the design process itself.
- Recently added application domain: Environmentally Benign Design and Manufacture

Overview of Topics

- Characterizing the simulation-based design problem from an information economic perspective
 - Imprecise probabilities: representation and decision-making (Jason Aughenbaugh)
 - Computation with imprecise probabilities (Morgan Bruns)
 - Representation of models: economic characteristics of simulation models (Rich Malak)
 - Trade-off between cost of executing the design process and value added to the product (Jay Ling)
- How to frame simulation-based design problems?
 - Branch & Bound methods for set-based design (Steve Rekuc)
 - Modeling and selecting design processes based on value of information (Jitesh Panchal)
- Reducing the cost of framing simulation-based design problems
 - Information knowledge modeling to reduce the cost of supporting design decisions (Manas Bajaj)

Relationship to Others in SRL

- Characterizing Decision Processes
 - Farrokh, Jitesh, Hae-Jin, Marco, ...
- Uncertainty Representation
 - Janet, Hae-Jin, Scott, Jamal, ...
- Knowledge and Model Repositories
 - David, Greg, Nsikan, Sungshik, ...
- EBDM
 - Bert, Scott, Felipe, ...

Presentation Order

- Jason
- Jay
- Rich
- Morgan
- Steve

Uncertainty Representations for Information Economics

Jason Aughenbaugh



28 June 2005

Motivation: Uncertainty Exists

- Estimates, models, measurements, etc. all involve uncertainty
- How can we represent uncertainty?
 - Probability theory is one formal mathematics for uncertainty
 - But: often large sets of frequency data are unavailable
- Can we be objective?
- Can we be precise?

Subjective Probabilities Prevail

- Frequentist interpretations fail to be useful in most engineering problems
- Aleatory probabilities: model randomness in empirical phenomena [1]
- Epistemic probabilities: model logical or psychological degrees of partial belief [1]

Should we represent the two using the same formalisms?

What formalisms are possible?

[1] Walley, J., 1991, *Statistical Reasoning with Imprecise Probabilities*, Chapman and Hall, New York.

The Need for Imprecision

- Epistemic probabilities should be stated only imprecisely when:
 - Evidence is incomplete or indeterminate
 - Information or beliefs conflict
 - Bounded rationality constrains assessment and elicitation of beliefs
 - Cost of thinking
 - Computing limits
 - Lack of accurate or sufficient introspection
 - Information is of limited relevance
 - Practical reason: value of information calculation, statistical data gathering example (more later)

Contributions/Results

- Demonstrated the value of using imprecise probabilities (DETC05)
 - Using Probability Boxes (p-boxes)
 - For a pressure vessel design example
 - Single design variable
 - Single uncertain parameter
 - High cost of failure (skews expected utility)
 - Across various levels of (statistical) information
 - Conclusion
 - For scarce information, very valuable
 - For large amounts of information, slight cost in performance
- Value of information calculations in engineering design
 - IMECE05 submitted, Jay will discuss

Highlights/Summary

- **Legacy**
 - Foundations of imprecise, subjective probabilities applied to engineering design problems
 - Identification and demonstration of potential and limitations of imprecise probabilities
 - Fundamental application of information economics in engineering design
- **Relation to other SRL work**
 - Scott Duncan (extreme uncertainty)
 - Hae-Jin Choi (uncertainty)
 - Jamal Wilson (resolution of indeterminacy)
 - Jitesh Panchal (model reuse)
 - Felipe Roman (? stay tuned)
 - 266 crowd
- **Expertise**
 - Philosophy of probability
 - Classical
 - Frequentist
 - Subjective
 - Imprecise probabilities
 - Dempster-Shafer/Evidence Theory
 - Value of Information
 - Tools
 - MATLAB
 - RiskCalc (see Morgan first)
 - CORE (don't bother using)
 - Plone/Zope

The Value of Information in Information Economics

Jay Ling

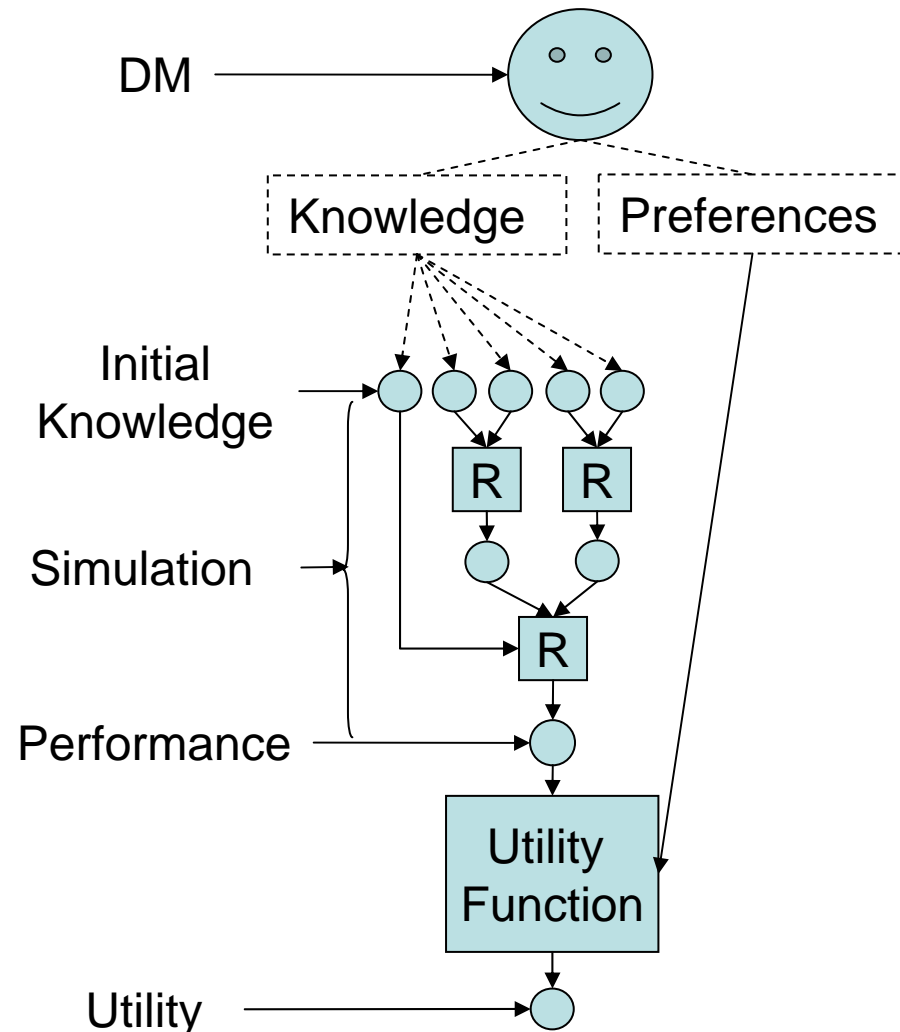


28 June 2005

Motivation: The Value of Information

- Information is gathered throughout the design process to support a decisions.
 - Benefits: DM acquires a better understanding of the problem which often leads to a better decision
 - Costs: Purchasing or locating, model construction, simulation, interpretation of the results
- Which of the available information gathering tools should be used? How can we know that we have gathered enough information?
- Context: Simulation Based Design

Simulation Based Design: Evaluation of a Design Alternative



- The uncertainty in the DM's knowledge and preferences causes uncertainty in the design utility.
- This uncertainty often leads to indecision. At which point the DM must either make the decision or gather additional information.

Information Economics

- Can Value of Information Theory guide simulation selection?
 - Has been used in cases in which the information source and current state of knowledge are known exactly.
 - How can it be applied when significant uncertainty exists?

Contributions/Results

- IMECE: Bounded the value of the next message from an information source (the results of a torsion test on the material).
 - Used Probability Boxes to represent the imprecision in the DM's knowledge about the information source.
 - Modified the Value of Information framework to incorporate imprecision.
 - For a pressure vessel design example (Jason)

Highlights/Summary

- **Legacy**
 - Methods for incorporating Value of Information Theory in simulation based design
- **Relation to other SRL work**
 - Jitesh Panchal (model fidelity)
 - Scott Duncan (extreme uncertainty)
 - Hae-Jin Choi (uncertainty)
 - Jamal Wilson (resolution of indeterminacy)
 - 266 crowd
- **Expertise**
 - Imprecise probabilities
 - Value of Information
 - Civil engineering
 - Philosophy of probability (Jason)
 - Tools
 - Maple
 - TI - 89

Characterization of Behavioral Models for Simulation-Based Design Problems

Rich Malak



Motivations: Reasoning about Models

- Want to formalize the properties of behavioral models so that we can reason about the models more effectively
- Problem context is value-of-information tradeoff analyses
 - Care about developing/using the *most valuable* model
 - Not necessarily the highest fidelity
 - Perform theoretical analyses to guide development of practical heuristics
- Lots of open questions:
 - What kinds of model properties are important to characterize?
 - What conclusions can engineers draw with them?
 - What representations are appropriate for the properties?
 - What methods are appropriate for performing characterization?
 - ...

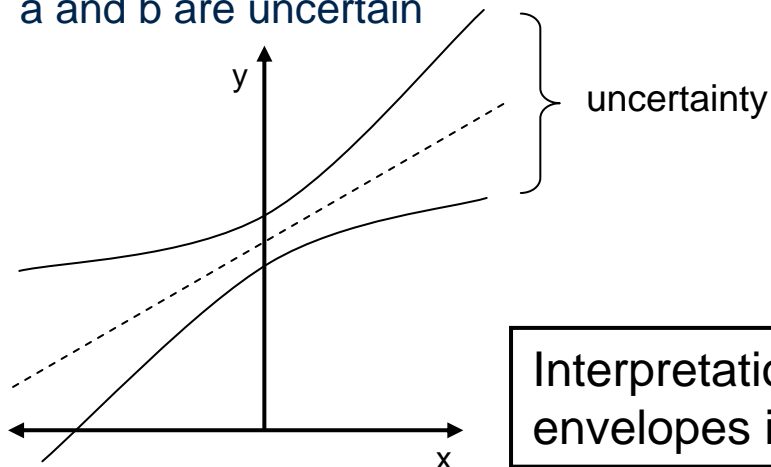
Some Model Properties to Investigate

- **Context**
 - A set of conditions over which a statement holds
 - Many properties will be “variant” in that they depend on the particular context
- **Uncertainty**
 - The degree to which a prediction generated using a model can differ from an observation under the “same” conditions
 - Depends on context
- **Cost**
 - Various costs associated with a model
 - E.g., execution, storage & retrieval, development & characterization, etc.
- **Validity**
 - Combination of context and uncertainty

Model Uncertainty

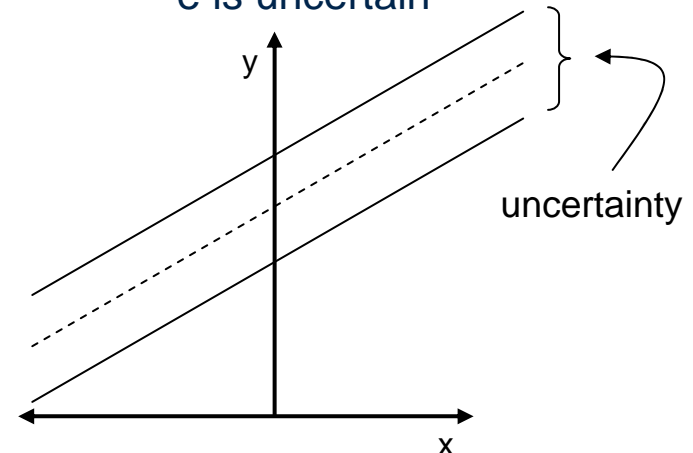
- Several complications arise once we move away from viewing models as certain
 - Where does the uncertainty “reside”: model parameters, a separate error parameter?
 - What assumptions are we really making? What are the semantics of a model and its predictions?
 - Can imprecise probabilities be useful?

$y = ax + b$,
 a and b are uncertain



Interpretation of
envelopes is important

$y = ax + b + e$,
 e is uncertain



Some Potential Applications

- **Model Reuse**
 - Prior work focuses on interoperability
 - Some in literature skeptical about value of reuse, but minimal investigation from value perspective
 - Distinct lack in work on formalizing model properties associated with validity and “usefulness”
- **Product Families/Platforms**
 - As design specifications are reused/adapted, so can behavioral models
 - Value-of-information principles to refine design process over time
- **High-risk Systems**
 - Uncertainty always a concern & often interested in extreme events
 - Meaningful characterization of models can improve credibility of simulation results & design process

Highlights/Summary

- **Legacy**

- Model properties for VOI tradeoff analyses
- Representations for model properties
- Methods for characterizing model properties

- **Related SRLiens (beyond 266)**

- Representation and reuse of knowledge and information
 - [Jitesh](#), [Greg](#), [Marco](#), [Nsikan](#), [Manas](#)
- Uncertainty
 - [Hae-jin](#), [Scott](#)

- **Expertise**

- Software and Languages
 - MATLAB, Dymola, DAKOTA, ModelCenter
 - Modelica and other modeling languages, general programming languages (C, Java, etc.)
 - Photoshop, The GIMP
- Theory, Methods and Other Tidbits
 - Model validation, prob. & stats, optimization, info/knowledge modeling
 - AI, machine learning, EE, CS
 - Poster design & printing

Computing with Imprecise Probabilities

Morgan Bruns



Motivation: Practical Propagation of Imprecise Probabilities

- Making design decisions depends on the successful propagation of P-box type uncertain variables.
- Pure P-box computations:
 - Explicit, analytic equations
 - Results are best-possible, rigorous
 - ***But*** cannot be applied towards “black box” models

Computing with Imprecise Probabilities

- The problem:

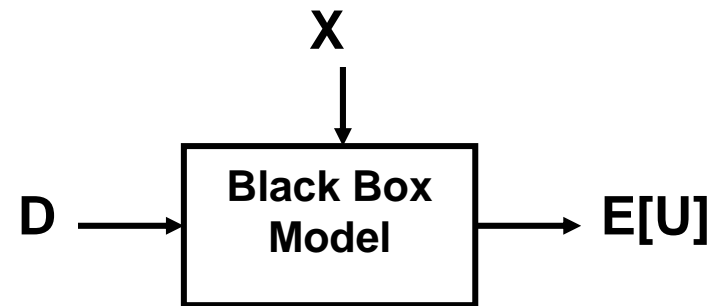
Given:

\mathbf{X} = Uncertain Parameters = $\{x_1, \dots, x_l\}$

\mathbf{D} = Design Variables = $\{d_1, \dots, d_n\}$

Find:

$E[U(\mathbf{D}, \mathbf{X})]$ = Expected Utility of Design = $[E_{\mathbf{D}, \mathbf{X}}(U), \bar{E}_{\mathbf{D}, \mathbf{X}}(U)]$

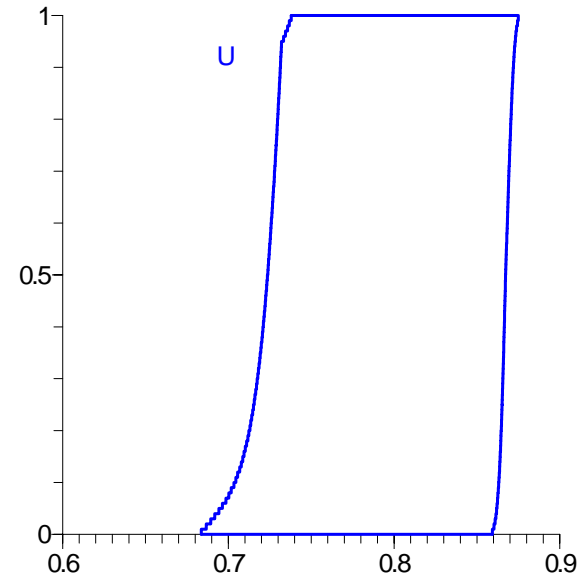
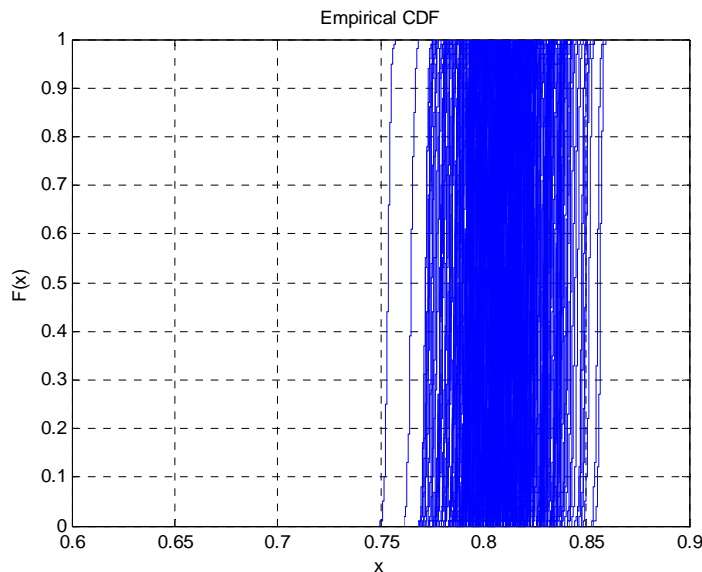


- The requirements:

- Applicable towards black box models
- Produce results close to “best possible bounds”
- Account for dependencies, or lack thereof
- Robust for variety of models and inputs

Possible Solutions/Preliminary Results

- Two-dimensional Monte Carlo:
 - Simple to implement, can wrap a “black box”



- Optimization/Monte Carlo Hybrid
- Sensitivity Analysis

Context in the SRL

- **Legacy**
 - Pragmatic methods for computing with imprecise probabilities
- **Relation to other SRL work**
 - Scott Duncan (extreme uncertainty)
 - 266 crowd
- **Expertise**
 - P-box computations
 - Dependence in probabilistic modeling
 - Imprecise probabilities
 - Risk Calc

Eliminating Design Alternatives under Epistemic Uncertainty

THE FOLLOWING **PREVIEW** HAS BEEN APPROVED FOR
THE SYSTEMS REALIZATION LABORATORY
BY STEVEN J. REKUC

Motivation: Uncertainty affects decision-making

- **Uncertainty exists**
- **Uncertain about design performance**
- **The impact:** Uncertainty limits the designer's ability to select a specific alternative
- **The approach:** The designer should choose a set of designs, eliminating those dominated alternatives
- **Toyota Success:** Set-Based Concurrent Engineering is used at Toyota, but has not been formalized.[1]

[1] Sobek, D. K. I. and A. C. Ward (1996). "Principles from Toyota's Set-Based Concurrent Engineering Process." *ASME Design Engineering Technical Conferences and Computers in Engineering Conference*, Irvine, California, August 18-22.

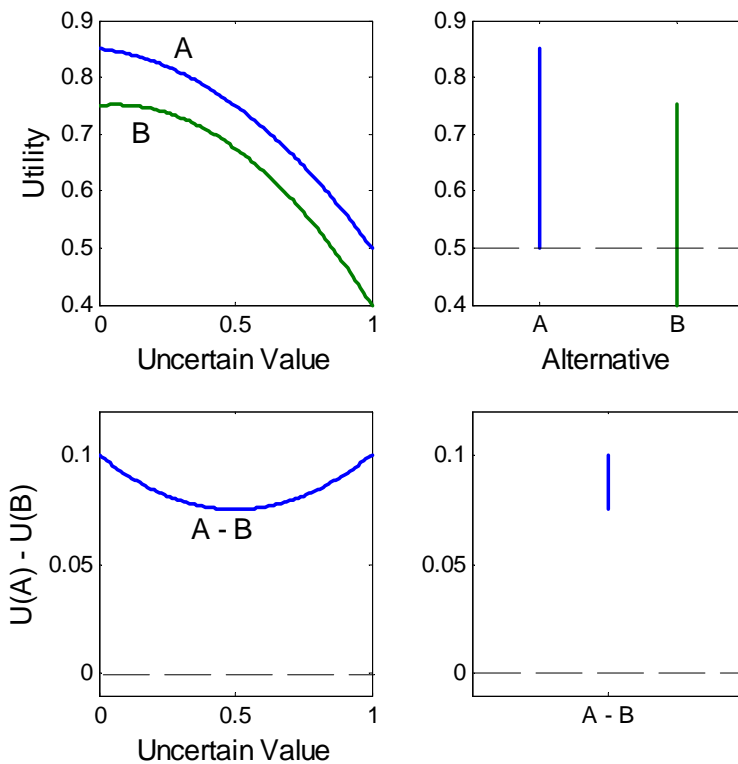
Elimination in the set-based approach

- **Overall Objective:** A formal approach to set-based design based on the Branch and Bound Algorithm
- **Components needed:**
 - Branching: define alternatives to decide on
 - Bounding: characterize performance
 - Eliminating inferior alternatives
 - Strategy: what order to investigate the branches
- **Problem:** The designer needs to eliminate design alternatives to converge toward a solution, and the designer needs to branch, bound, and search the space to allow more elimination.
- **Question:** Under conditions of epistemic uncertainty, how should one eliminate design alternatives?
- **Hypothesis:** One should eliminate design alternatives rationally by comparing them to a detailed, specific reference design to account for shared uncertainty.

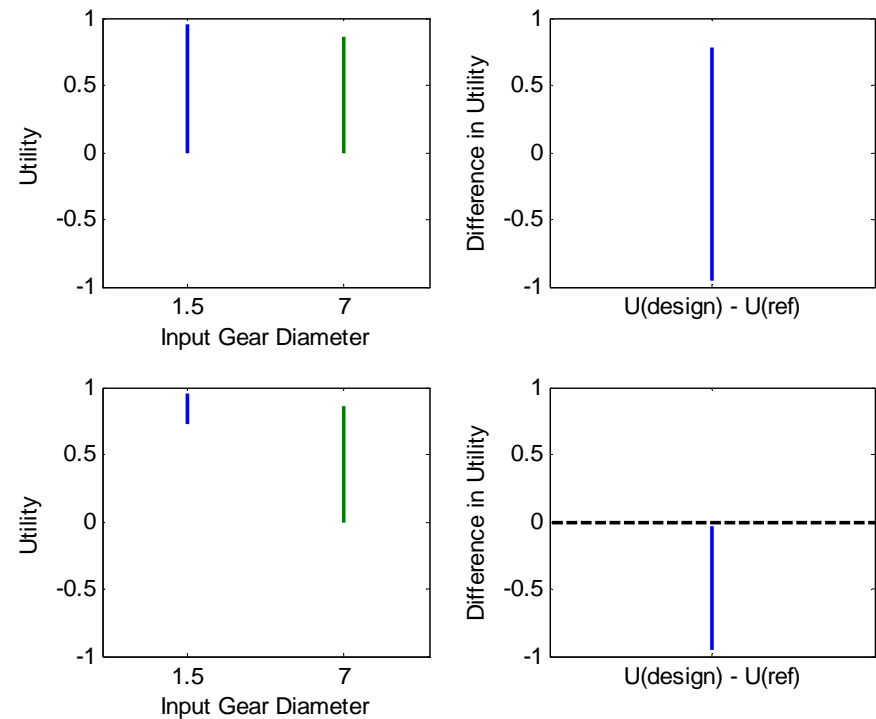
Elimination Method

Rational Elimination: if $\bar{U}(A_i) < \underline{U}(A_j)$ then eliminate A_i

Shared Uncertainty:



Detailed Reference Design:



Contribution

- Eliminate designs under uncertainty
 - Elimination method for intervals
 - Shared uncertainty for better elimination
 - Detailed, specific reference design
 - Demonstrated in Gearbox and Beam Designs
- Concept for a B&B design approach
 - Determined the requirements
 - Needs significant future work

Summary

- **Legacy**
 - Elimination method for intervals
 - Reference design to improve elimination / decision-making
 - B&B concept for a formal set-based design method
- **Relation to SRL work**
 - Scott Duncan (uncertainty)
 - Jamal (decision-making with intervals)
 - Jitesh (design process and intervals)
 - Hae-Jin (uncertainty)
 - Marco (design process)
- **Expertise:**
 - Branch and Bound
 - Set-Based Design
 - Uncertainty
 - Gear Design and Modeling
 - Info-Gap Decision Theory
 - Programs:
 - Matlab / Simulink
 - Camtasia (Video Tutorials)
- **World Premiere:**
 - Thursday, July 7th – 1pm
 - In a MaRC room near you

Thanks...Any Questions?